King Saud University
Sustainable Energy Technologies
Center (SET)

BIOMASS GROUP

Biomass to Energy Conversions

-Thermochemical Processes-

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Outline

- **Introduction**

1. Energy Context
2. Biomass as Renewable Energy Resources
3. Bioenergy

- **Biomass characteristics**

1. Biomass composition
2. Thermo-physical properties

- **Biomass Thermal Conversion**

1. Principals
2. Gasification technology
3. Pyrolysis technology

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Energy context

World population is rising (8.3 billion by 2030)

↓

Global energy demand increase

↓

GHG emissions to the atmosphere (especially CO_2 and methane)

↓

- Renewable energy offer a good mechanism to reduce carbon emissions
- Energy efficient systems for more economy

Towards sustainability

Biomass as a renewable energy resource

- Biomass is biological organic matter derived from living or recently-living organisms
- Biomass is an extremely important energy source, available nearly everywhere
- Biomass encompasses a large variety of materials, including wood from various sources, agricultural and industrial residues, and animal and human waste
- Bioenergy is the energy contained (stored) in biomass

- Two forms of biomass

Raw: forestry products, grasses, crops, animal manure, and aquatic products (seaweed)

Secondary: materials that undergone significant changes from raw biomass. Paper, cardboard, cotton, natural rubber products, and used cooking oils.

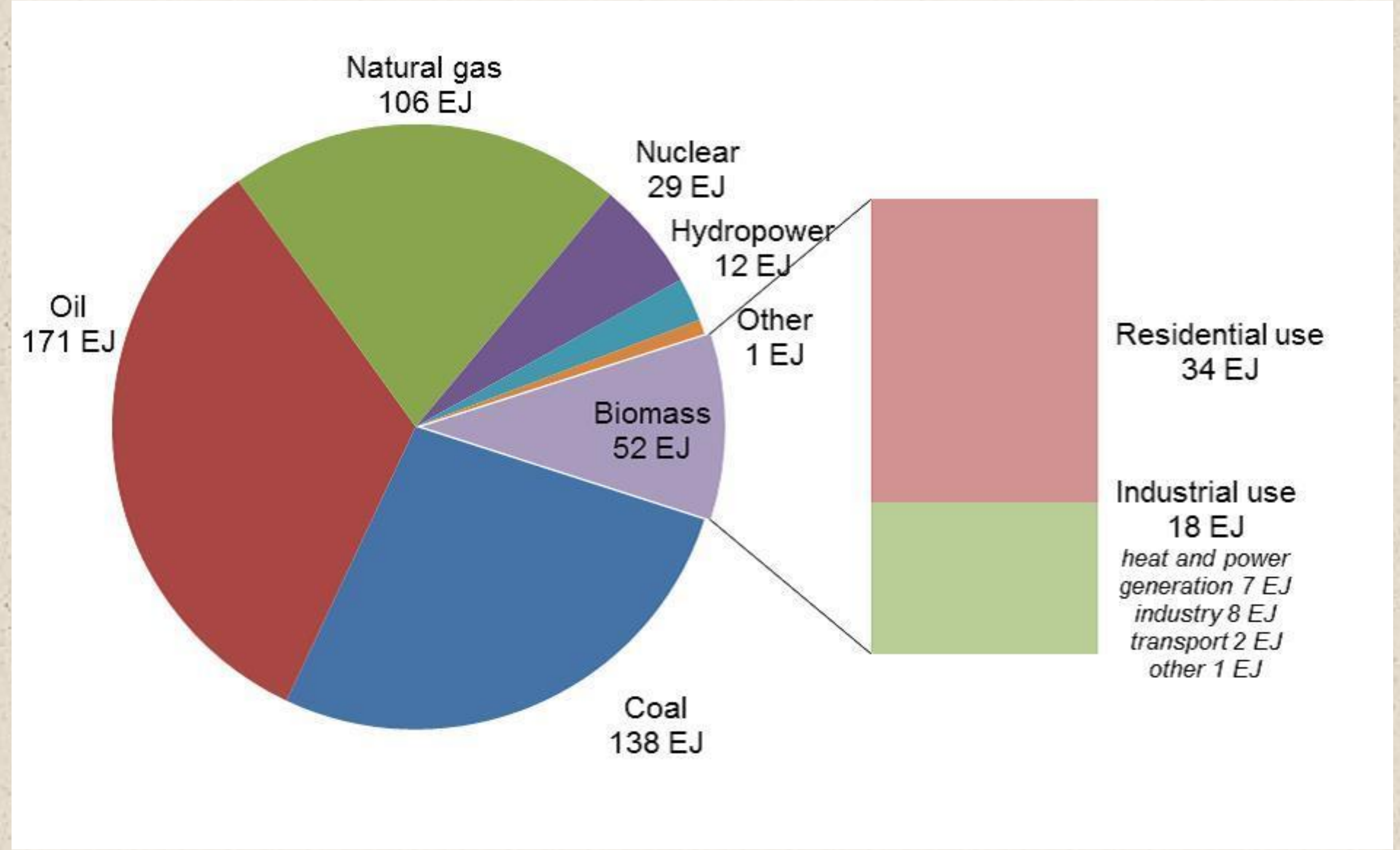
Biomass as a renewable energy resource

Bioenergy

- Bioenergy is the energy retrieved from biomass sources. It is the largest used renewable energy resource in the world
- Large bioenergy potential: Biomass resource is widely available and diversified in the Kingdom: Livestock waste, Municipal and Industrial effluents (paper, plastic, food, …etc.), Poultry waste, Sewage sludge
- Bioenergy is a significant mean for waste disposal to prevent environmental pollution and allow economic stability
- Main Technologies:
  - Biogas based power plant technology
  - Gasification power plant technology
  - Biodiesel and Bioethanol Plants technology

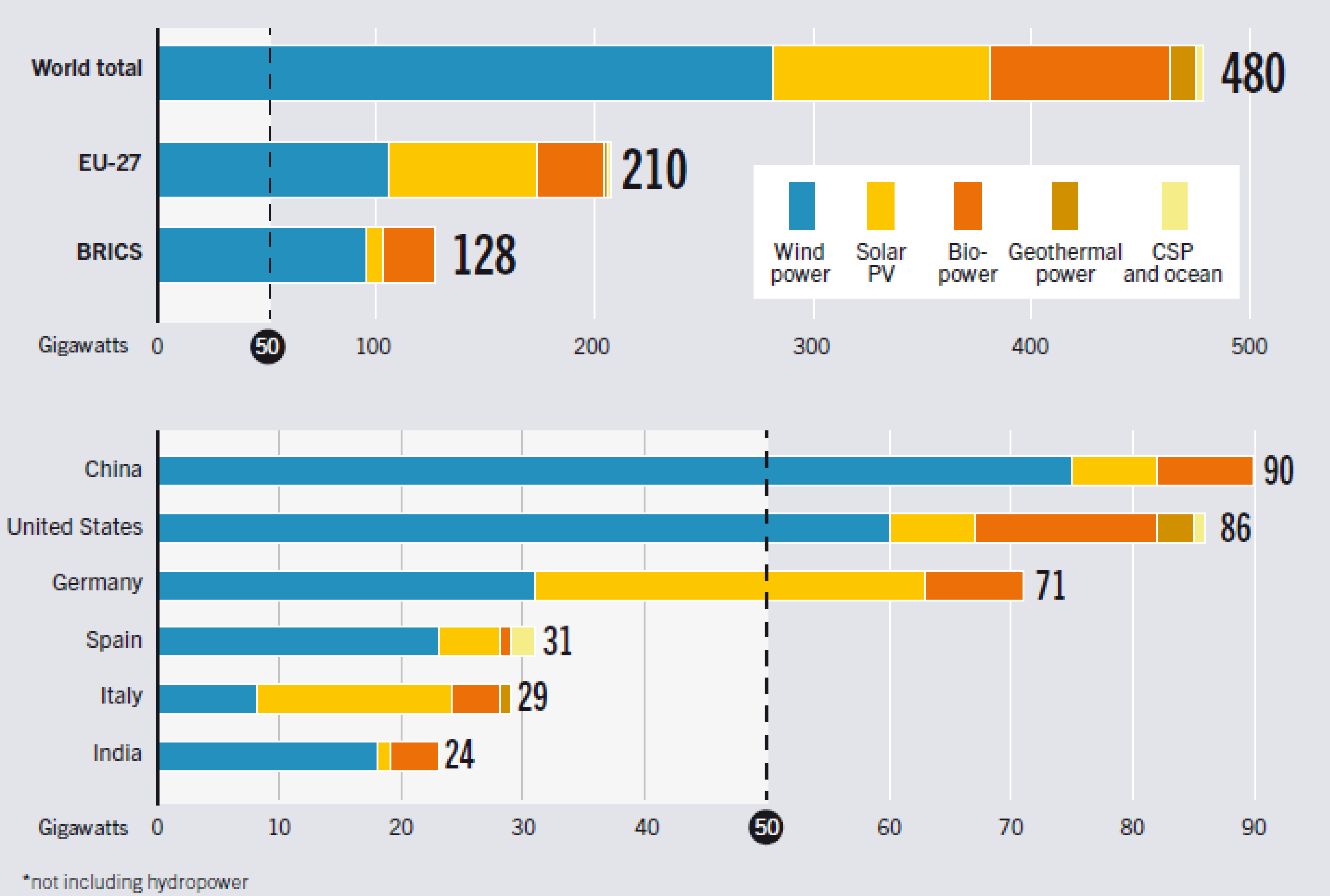
Bioenergy

Biomass provides more than 10 % of Global energy use (International Energy Agency, 2013)



Bioenergy

Renewable and Bio-Power Capacities in World (International Energy Agency, 2012*)



Bioenergy

Advantages:

- Biomass reduce the dependence on fossil fuels
- It provides an inexpensive and readily available source of energy, and chemicals
- It offers another major benefit to sustainability namely a pathway to manage municipal and agricultural waste
- Processing biomass materials for fuel reduce the environmental hazard
- Biomass provides an effective low Sulphur fuel.
- It has many derived products that may substitute those of plastics and other products
- It has many applications for remote area

Disadvantages:

- Biomass has low energy content compared to coal and petroleum derived fuels
- Intensive cultivation may stress water resource and deplete soil nutrients
- It has high cost of transportation and pre-treatment

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Biomass Composition

Biomass is composed from carbohydrate polymers (cellulose and hemicellulose), aromatic polymers (Lignin), proteins and fats (lipids)

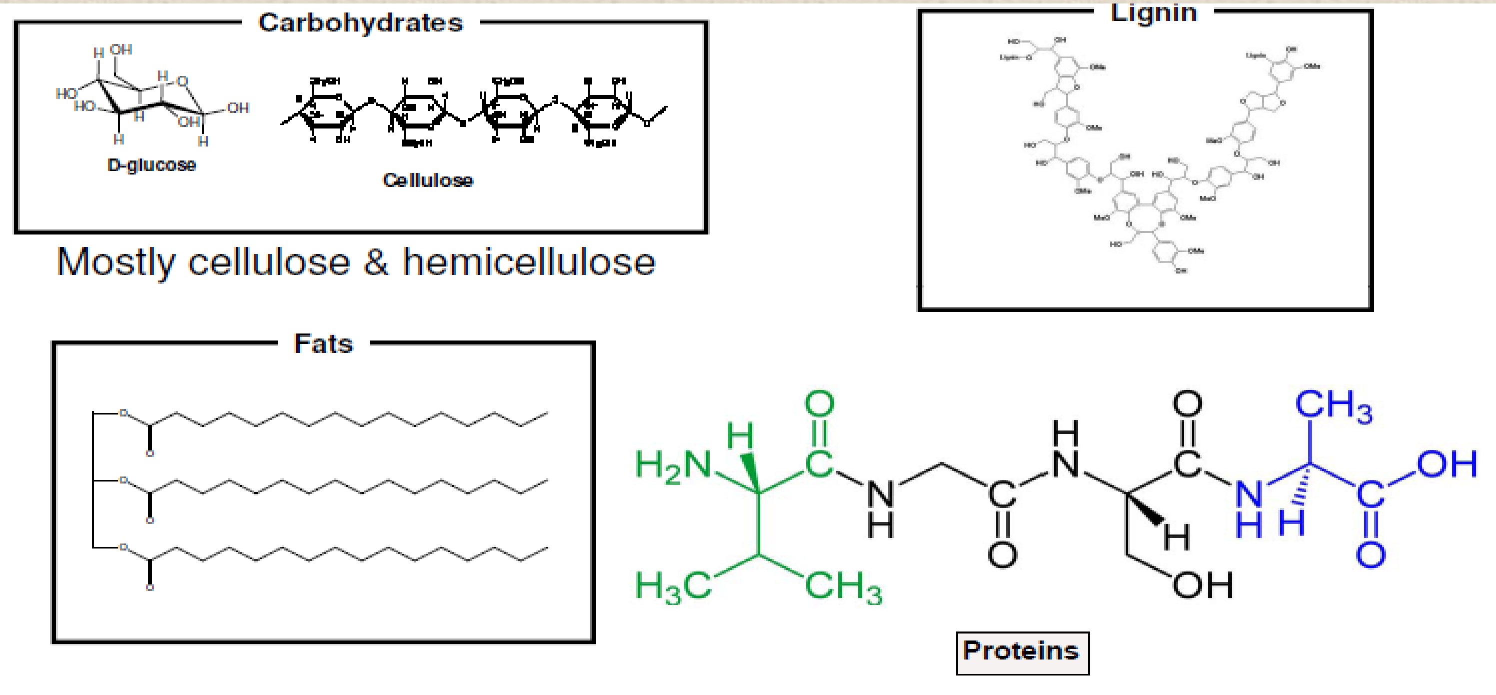
Cellulose ($C_6H_{10}O_5$) is the most important structural component of the primary cell wall of green plants and most abundant organic polymer on earth

Hemicellulose present with cellulose in almost all plant cell walls

Cellulose is crystalline, strong and resistant to decomposition in presence of heat, but hemicellulose has a little strength in front of heat

Unique characteristic of biomass as the only renewable and carbon based resource, makes it more attractive for energy purposes

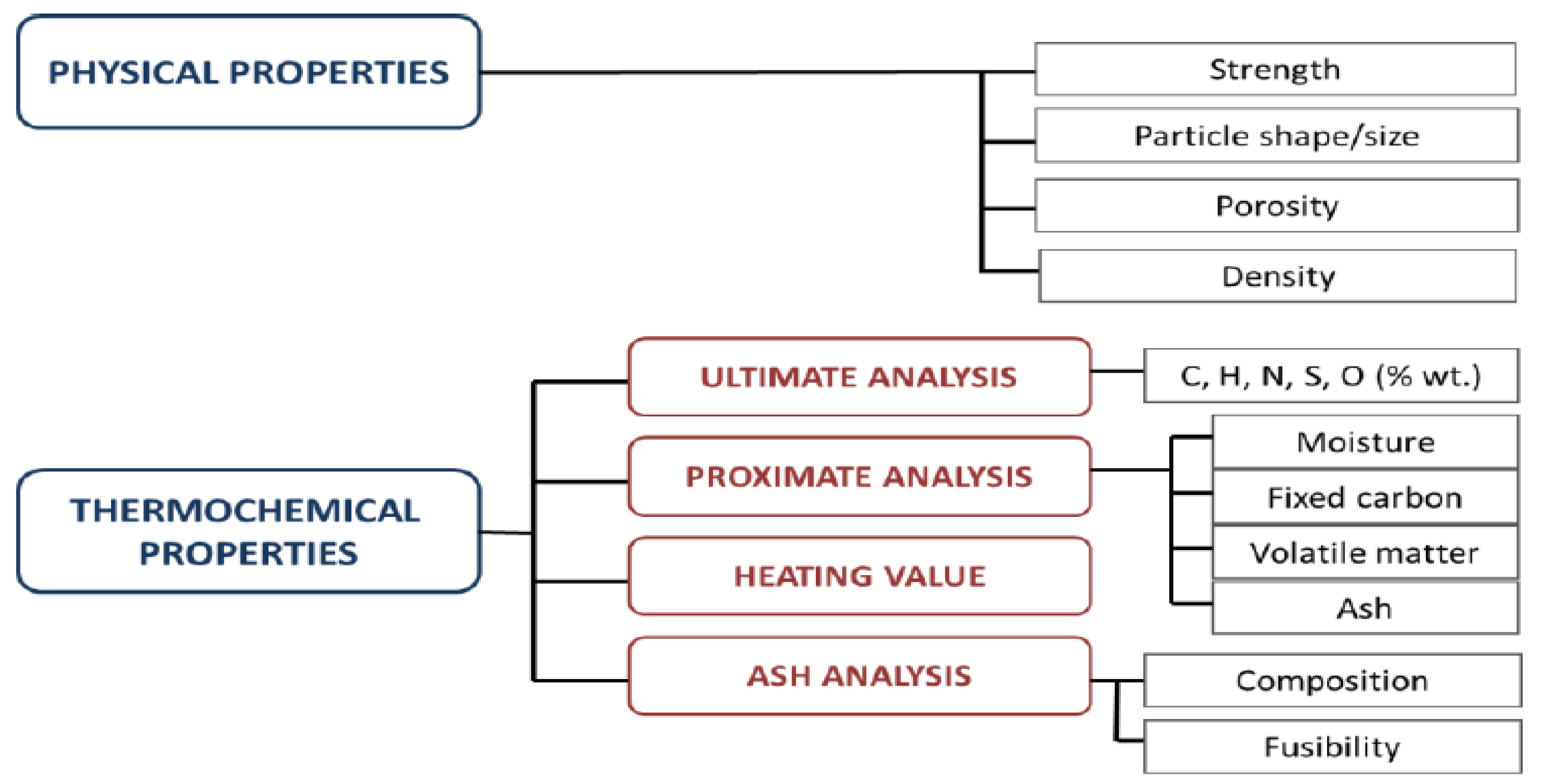
Divided into wet and dry biomass



Biomass Composition

Biomass	Lignin (%)	Cellulose (%)	Hemicellulose (%)
Softwood	27 – 30	35 – 42	20 – 30
Hardwood	20 – 25	40 – 50	20 – 25
Wheat straw	15 – 20	30 – 43	20 – 27
Switchgrass	5 – 20	30 – 50	10 – 40
Animal manure	5 – 8	10 - 20	15 – 22
Newspaper	18 – 30	40 – 55	25 – 40
Sorted refuse (MSW)	20	60	20

Thermo-physical properties



Thermo-chemical properties

Proximate analysis

Procedure steps:

1. Heat 1 hour at 104 ^{o}C to 110 ^{o}C. Report waste losses
2. Ignite in a covered crucible for seven minutes at 950 ^{o}C and report the weight loss (combined water, hydrogen, and the portion of the carbon initially present as or converted to volatile hydrocarbons) as volatile matter.
3. Ignite in an open crucible at 725 ^{o}C to constant weight and report weight loss as fixed carbon.
4. Report the residual mass as ash.

Ultimate analysis

Ultimate analysis refers to routine that report **mass content of several elements**: Carbon, Hydrogen (other than in moisture or combined water), oxygen, total sulfur, nitrogen, chlorine and ash. The testing method uses an elemental analyzer which consist of a system of oxidation and reduction chambers related to a Specific detection system

Thermochemical analysis

In combustion systems, **heat of reaction** is an important factor. This property can be obtained experimentally using a **bombe calorimeter** where a small quantity (sample) is burned with sodium peroxide in a heavy-walled, sealed container immersed in water.

Thermo-chemical properties

Proximate, ultimate composition and heating values (HHV) of some biomass feedstocks

	Ultimate Analysis (wt% dry basis)						Proximate Analysis (wt% dry basis)			
	C	H	N	O	S	Ash	Moisture	Volatiles	Fixed Carbon	Heating Value HHV (MJ/kg)
Agricultural Residues										
Sawdust	50	6.3	0.8	43	0.03	0.03	7.8	74	25.5	19.3
Bagasse	48	6.0	-	42	-	4	1	80	15	17
Corn Cob	49	5.4	0.4	44.6	-	1	5.8	76.5	15	17
Short Rotation Woody Crops										
Beech Wood	50.4	7.2	0.3	41	0	1.0	19	85	14	18.4
Herbaceous Energy Crops										
Switchgrass	43	5.6	0.5	46	0.1	4.5	8.4	73	13.5	15.4
Straw	43.5	4.2	0.6	40.3	0.2	10.1	7.6	68.8	13.5	17
Miscanthus	49	4.6	0.4	46	0.1	1.9	7.9	79	11.5	12
Municipal Solid Waste										
Dry Sewage	20.5	3.2	2.3	17.5	0.6	56	4.7	41.6	2.3	8
Coals										
Subbituminous	67.8	4.7	0.9	17.2	0.6	8.7	31.0	43.6	47.7	24.6
Bituminous	61.5	4.2	1.2	6.0	5.1	21.9	8.7	36.1	42.0	27.0

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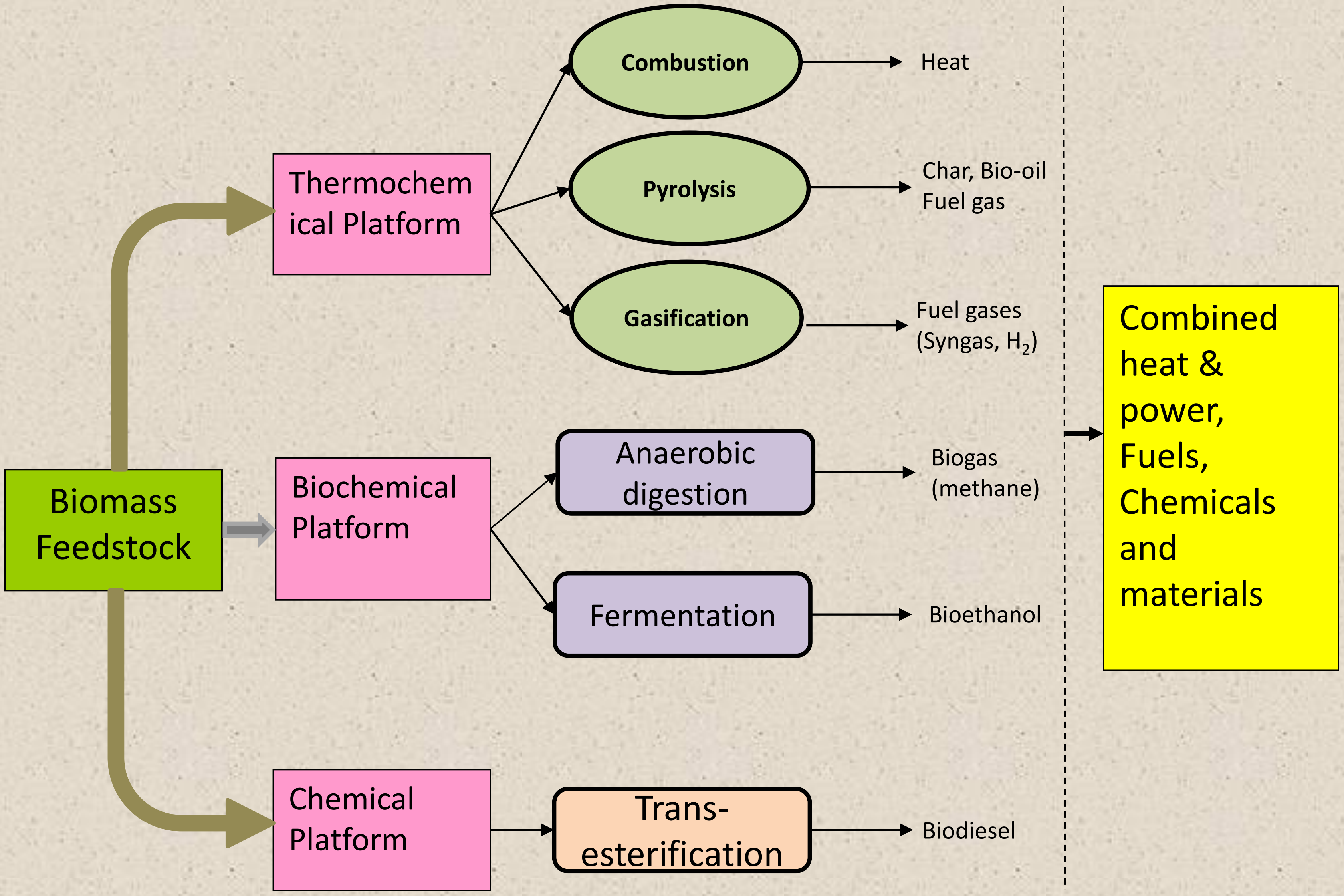
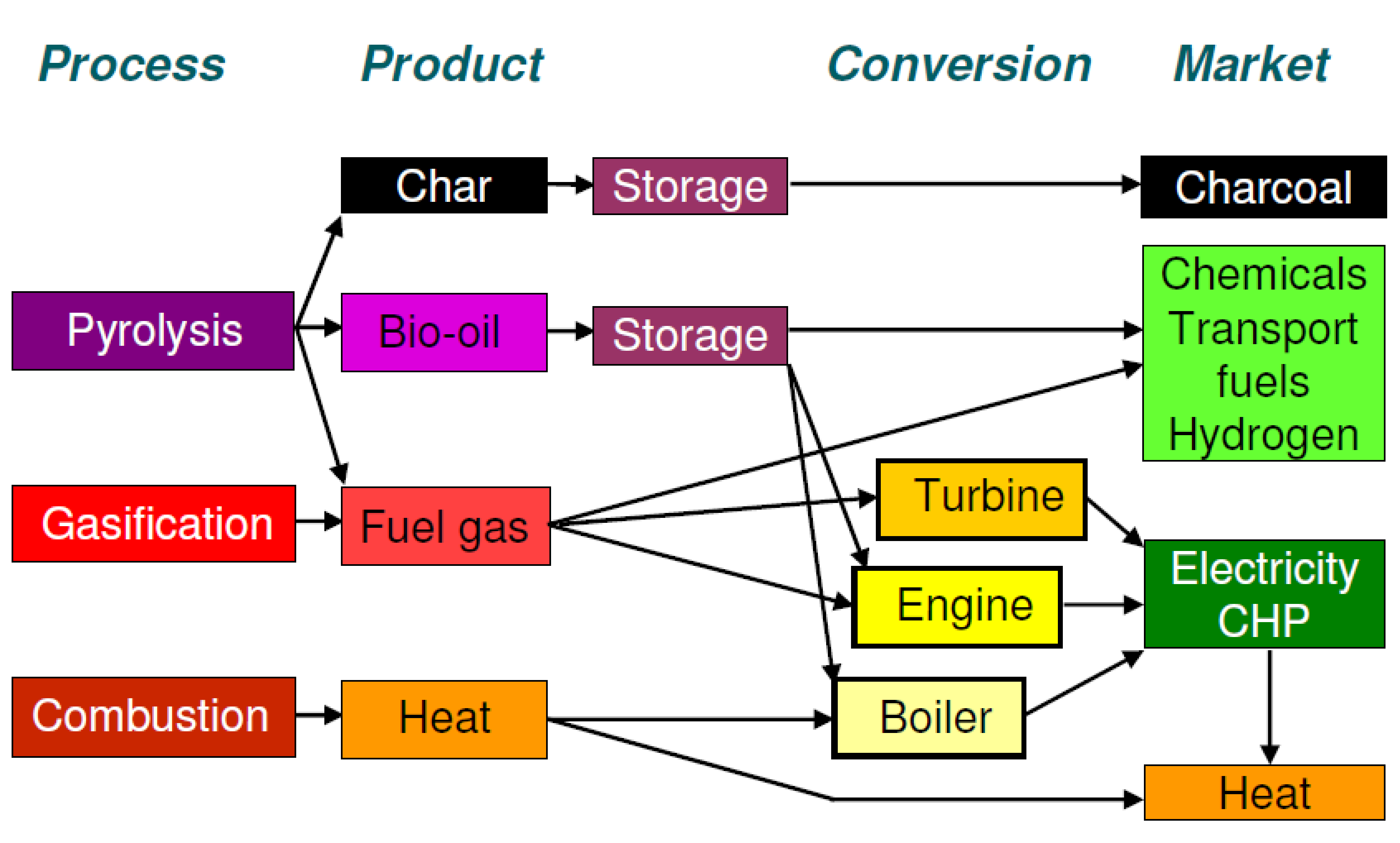
General Bioenergy Production Routes

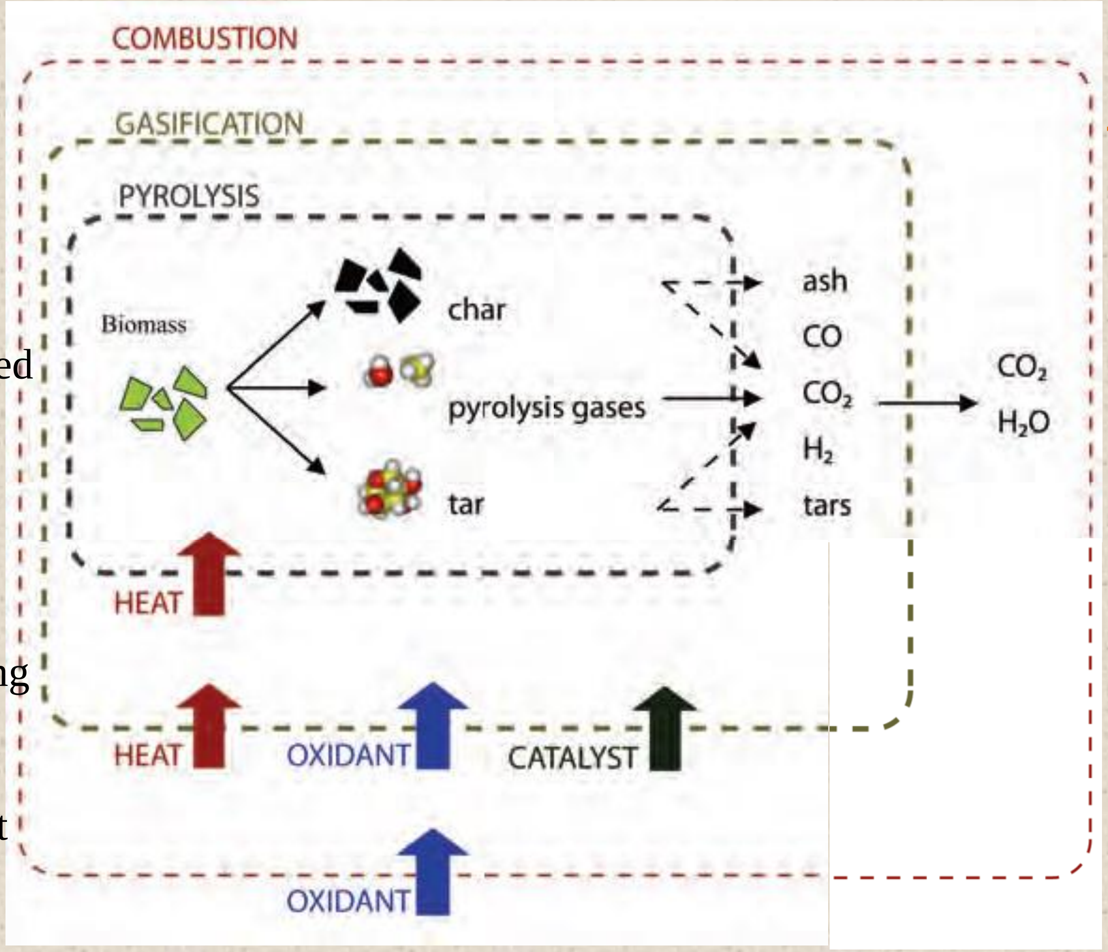


Thermochemical conversion options



Thermochemical conversion principals

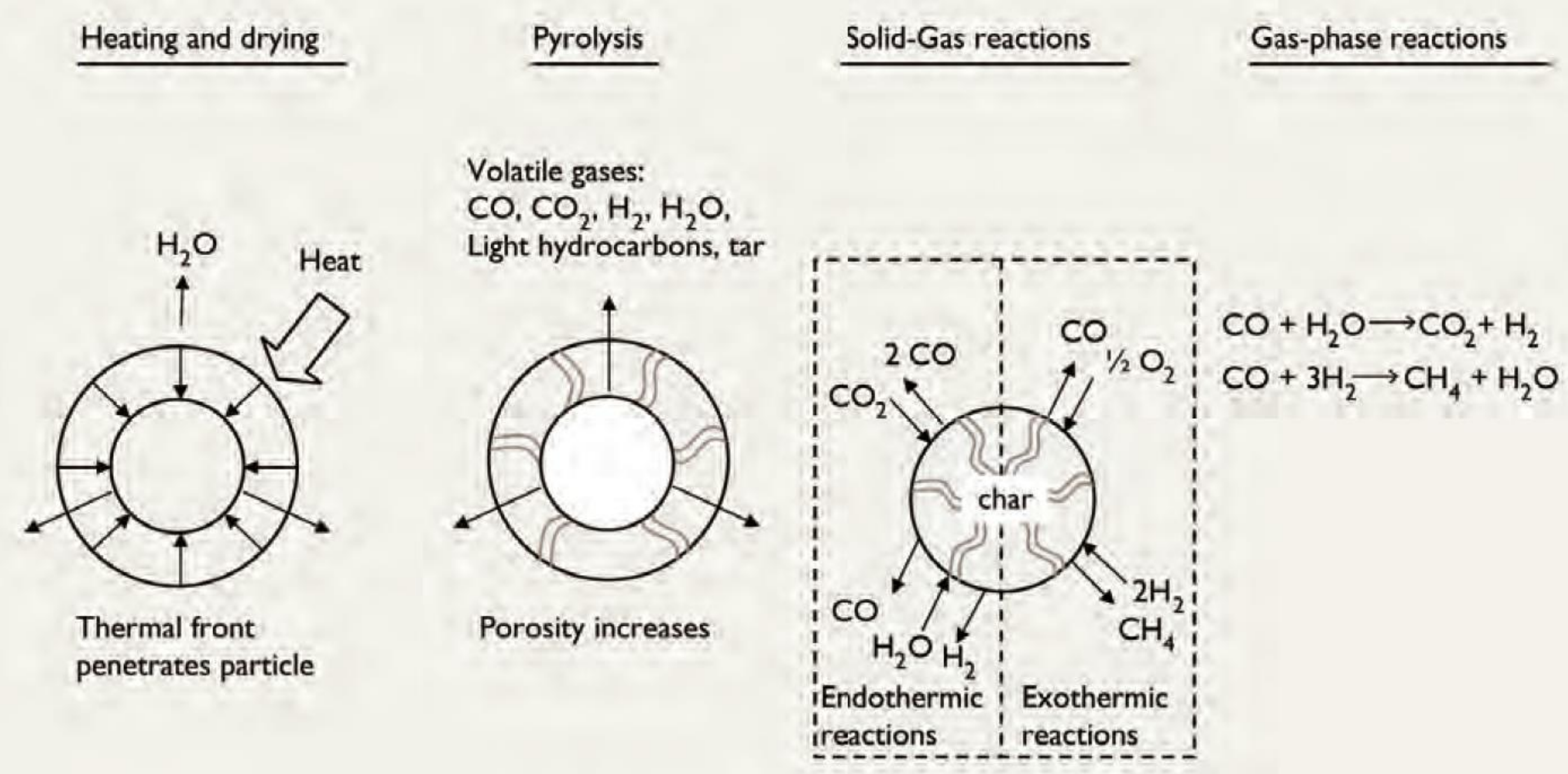
Pyrolysis
- First step in combustion and gasification processes
- The feedstock is heated in a reactor in the absence of air or oxygen
- Moisture and other volatiles are released above 100 °C
- The pyrolysis process occurs mostly between 300 and 400 °C yielding:
Pyrolysis gas (CO, CO2, H2, CH4, light HC)
Synthetic oil (Tars) obtained after cooling of condensable vapors including water, methanol, heavy HC, etc.
Char (carbonaceous solid and other inert materials.



Gasification
- The conversion of solid fuel is carried out at higher temperatures – 750 to 1200 °C and in a controlled atmosphere with sub-stoichiometric conditions of oxidant.
- The process is endothermic
- Gasification involves 4 steps:
Drying: moisture
Pyrolysis: volatiles, lights HC and tar
Solid-phase reaction: combustion of Solid carbon into CO, H_2 and CH_4
Gas phase reaction: reduction of CO

Combustion
- Rapid and complete oxidation of the solid fuel
- Main products: CO_2 and water
- High temperatures over 1200 °C

Gasification mechanism



Gasification mechanism

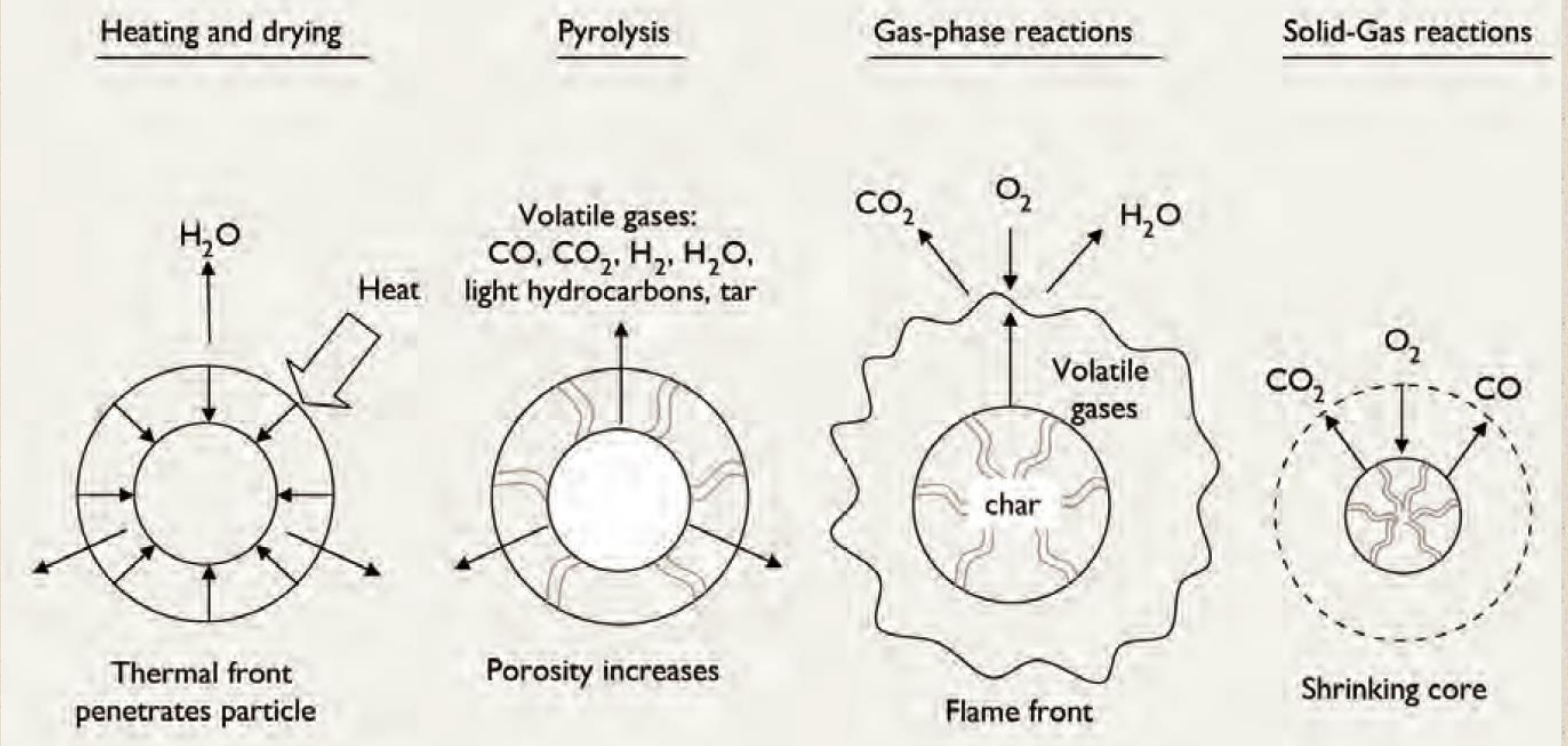
Solid-Gas reactions

Carbon – Oxygen reaction:	$C + 0.5 \cdot O_2 \leftrightarrow CO$	$\Delta H_r = -110.5\ kJ/mol$
Bouduard reaction:	$C + CO_2 \leftrightarrow 2CO$	$\Delta H_r = 172.4\ kJ/mol$
Carbon – Water reaction:	$C + H_2O \leftrightarrow H_2 + CO$	$\Delta H_r = 131.3\ kJ/mol$
Hydrogenation reaction:	$C + 2H_2 \leftrightarrow CH_4$	$\Delta H_r = -74.8\ kJ/mol$

Gas-phase reactions

Carbon monoxide – Oxygen reaction:	$CO + \frac{1}{2}O_2 \rightarrow CO_2$	$\Delta H_r = -281\ kJ/mol$
Water – Gas shift reaction:	$CO + H_2O \leftrightarrow H_2 + CO_2$	$\Delta H_r = -41.1\ kJ/mol$
Methanation reaction:	$CO + 3H_2 \leftrightarrow CH_4 + H_2O$	$\Delta H_r = 172.4\ kJ/mol$

Combustion mechanism



Comparison: combustion, gasification, pyrolysis

	Combustion	Gasification	Pyrolysis
Oxidizing Agent	Greater than stoichiometric supply of oxygen	Less than stoichiometric oxygen or steam as the oxidizing agent	Absence of oxygen or steam
Typical Temperature Range with Biomass Fuels	900 C to 1200 ^{o}C	800 to 1200 ^{o}C	350 to 600 ^{o}C
Products	Power, heat, soil amendments, and other co-products	Power, heat, combustible gas, chemical feedstocks, hydrogen, biochar, soil amendments	Power, heat, liquid fuel (bio-oil), combustible gas, chemical feedstocks, soil amendments, biochar
Principle Components of produced Gas	CO2 and H2O	CO and H2	CO and H2
Technology status	Mature	Deployment, emerging into commercialization	Demonstration

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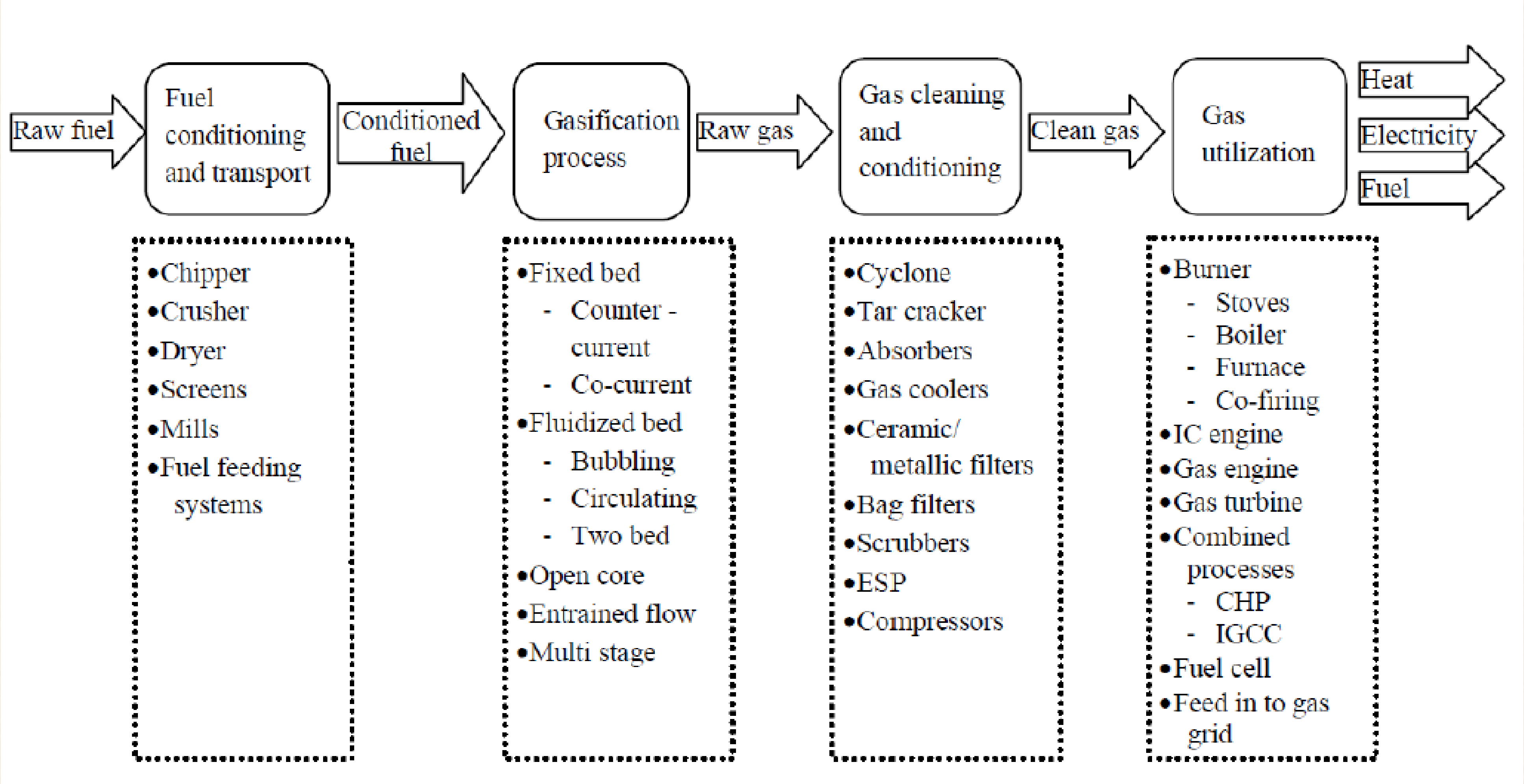
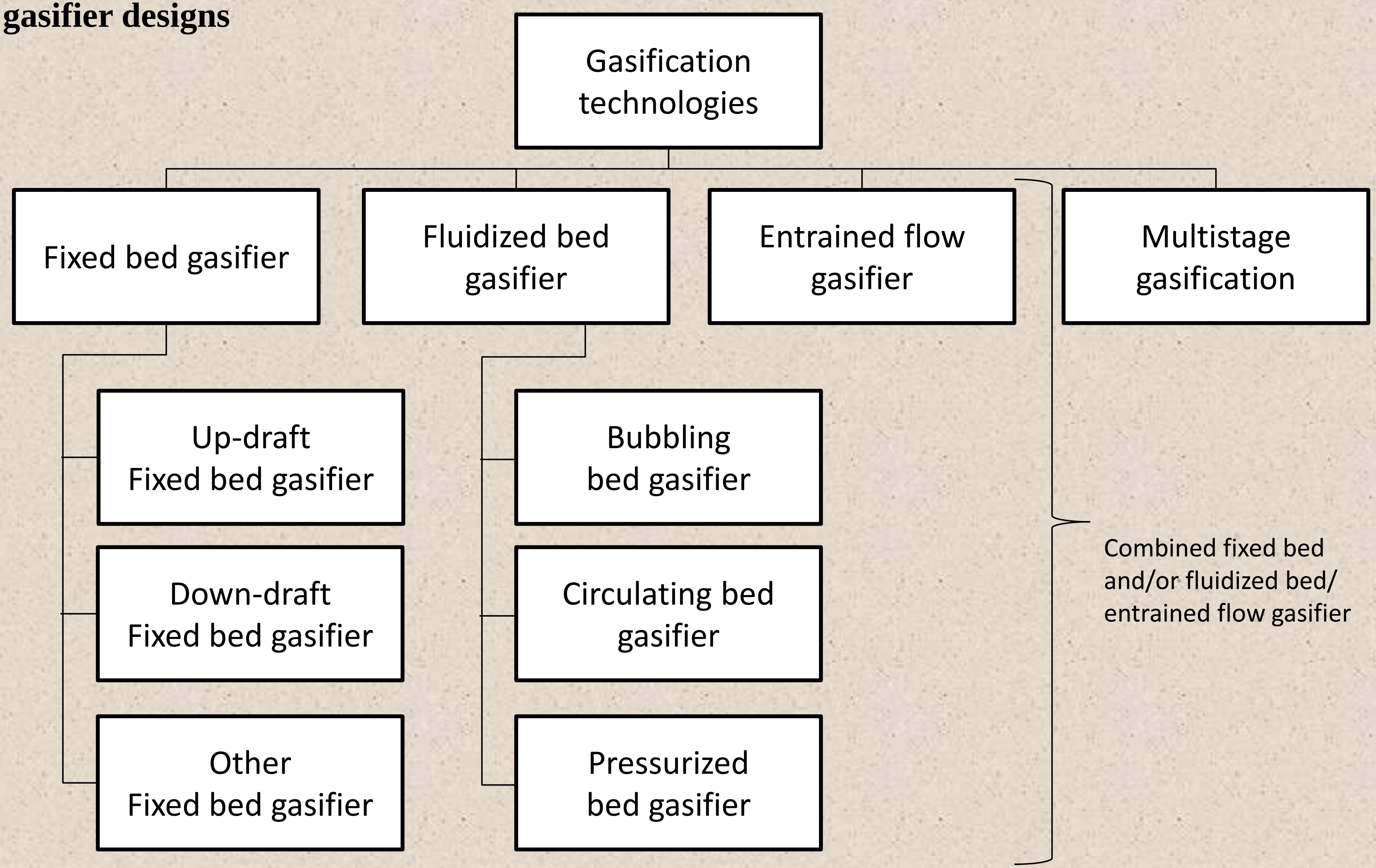
Basic process steps of a biomass gasification plant



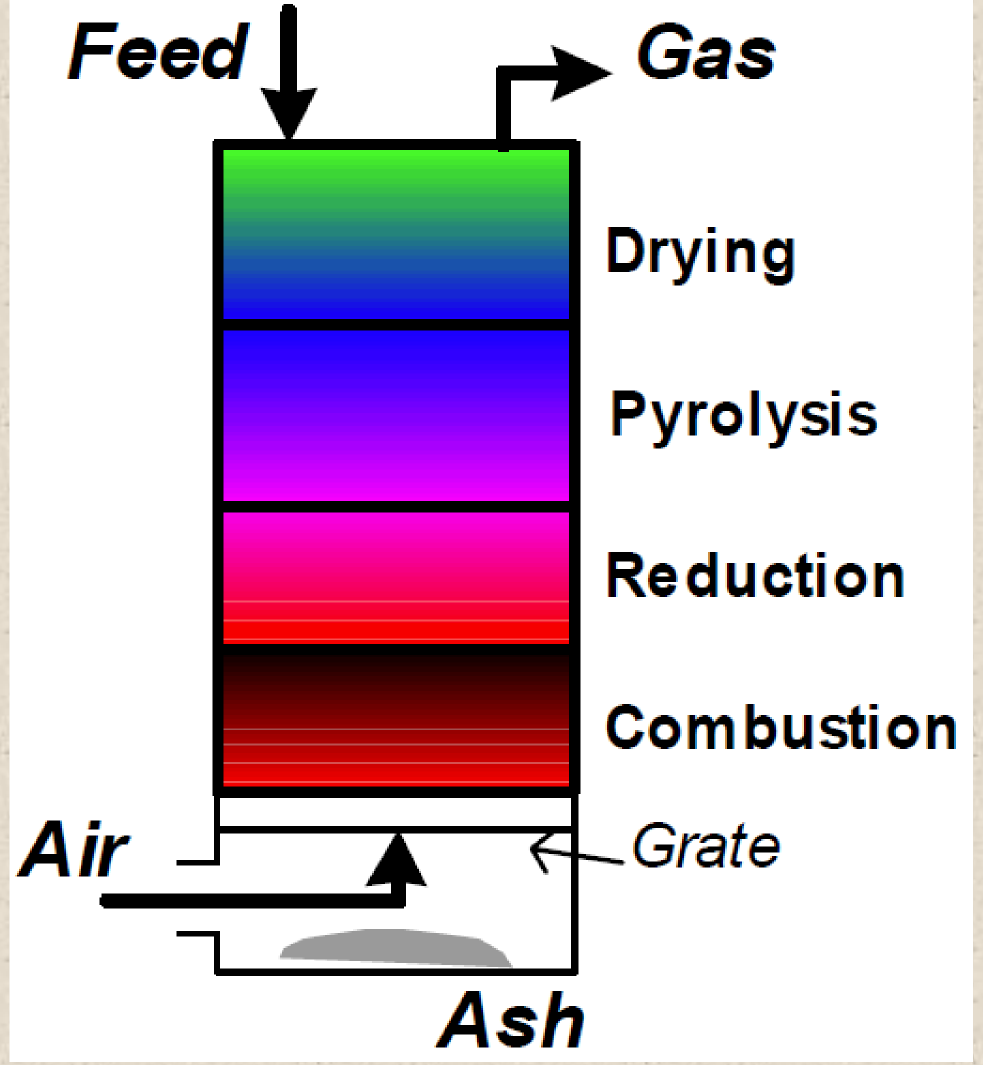
Overview of the different gasification technologies

Depending on the end application of the product gas and plant size, there are different gasifier designs



Gasifier types

Updraft Gasifier



- The gasification agent is added at the bottom, flowing in counter-current configuration with the feedstock, which is introduced in the top
- The fuel passes successively through drying and pyrolysis where it is decomposed into volatile gases and solid Char
- After pyrolysis has finished, the char is reduced by endothermic gasification reactions
- Combustion of char occurs near the grate and the hot combustion gases transfer heat to the rest of the process
- Char conversion is high, as the char reacts with oxygen as a last sub-process and char combustion reaction is faster than the char gasification reactions

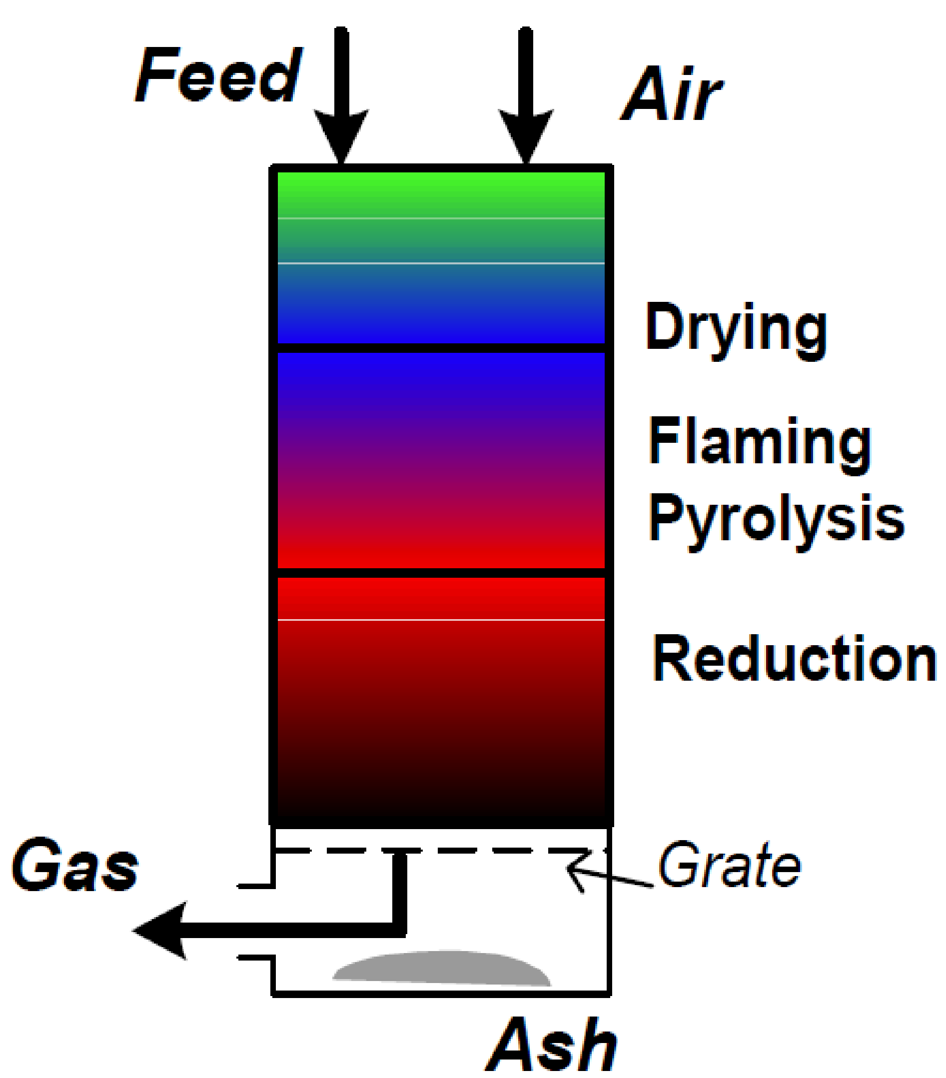
Gasifier types

Characteristics of Updraft Gasifiers

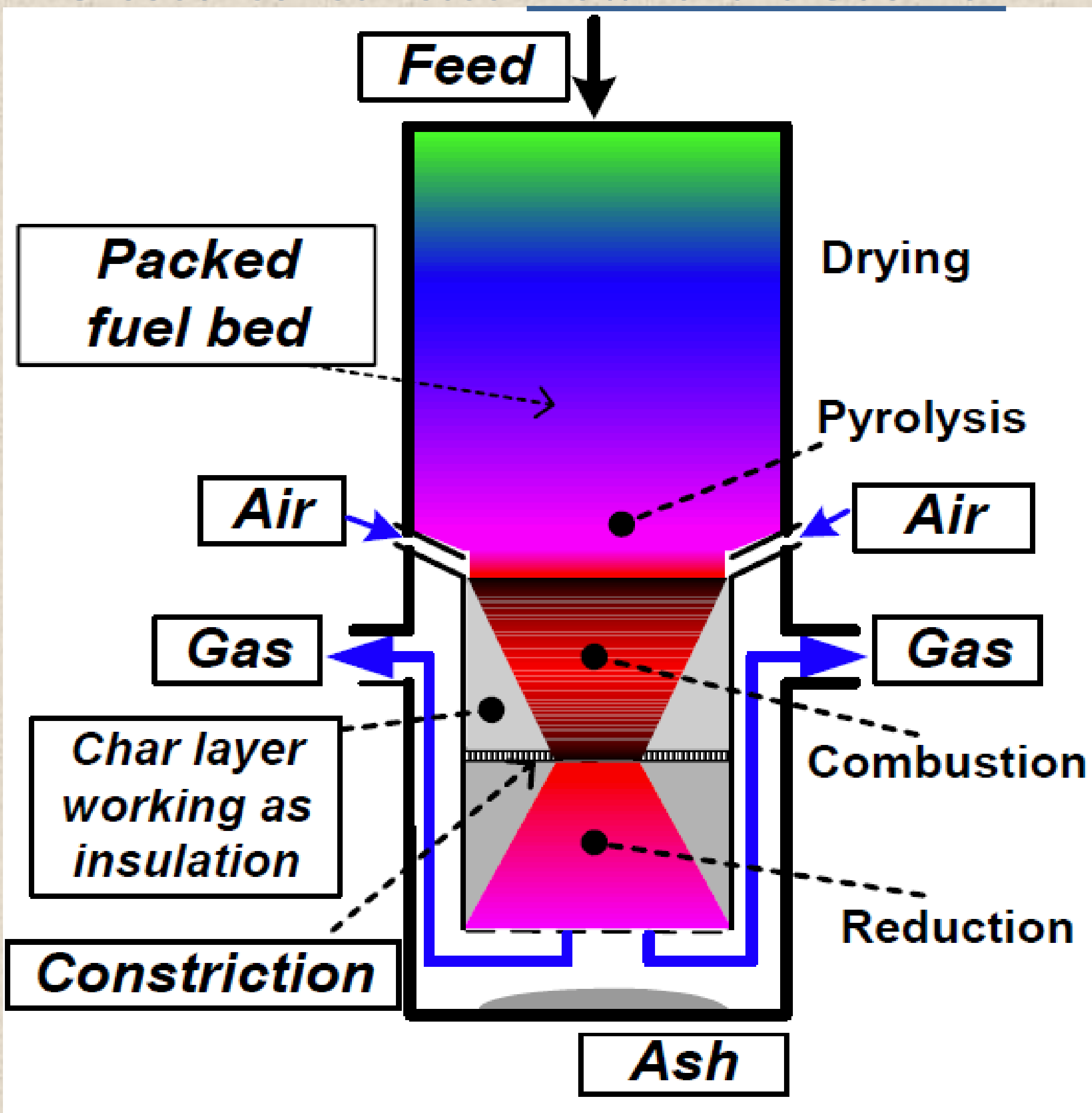
- **Char conversion is high, as the char reacts with oxygen as a last sub-process and char combustion reaction is faster than the char gasification reactions**
- **The gasification efficiency is high due to high char conversion and due to that the gas exit temperature is relatively low (300-400°C).**
- **As pyrolysis takes place at rather low temperature, tar and methane production are significant**
- **As the pyrolysis gases do not pass a combustion zone, instead leaving with the product gas, the tar content of the product gas is high**
- **The gas has relative high heating value compared to other gasification technologies as for the high tar content in the product gas**
- **The gas is suitable for direct combustion applications, such as a small steam boiler or for ceramic industry. Using the gas in an IC-engine requires extensive gas cleaning**
- **The gasifier construction is robust and relatively easy in operation**
- **The gasifier can use fuel with moisture content up to 60 % (wet basis). However, the higher the moisture content, the lower the gasification efficiency. The gasifier accepts size variations in the feedstock**

Gasifier types

Open-core Downdraft Gasifier



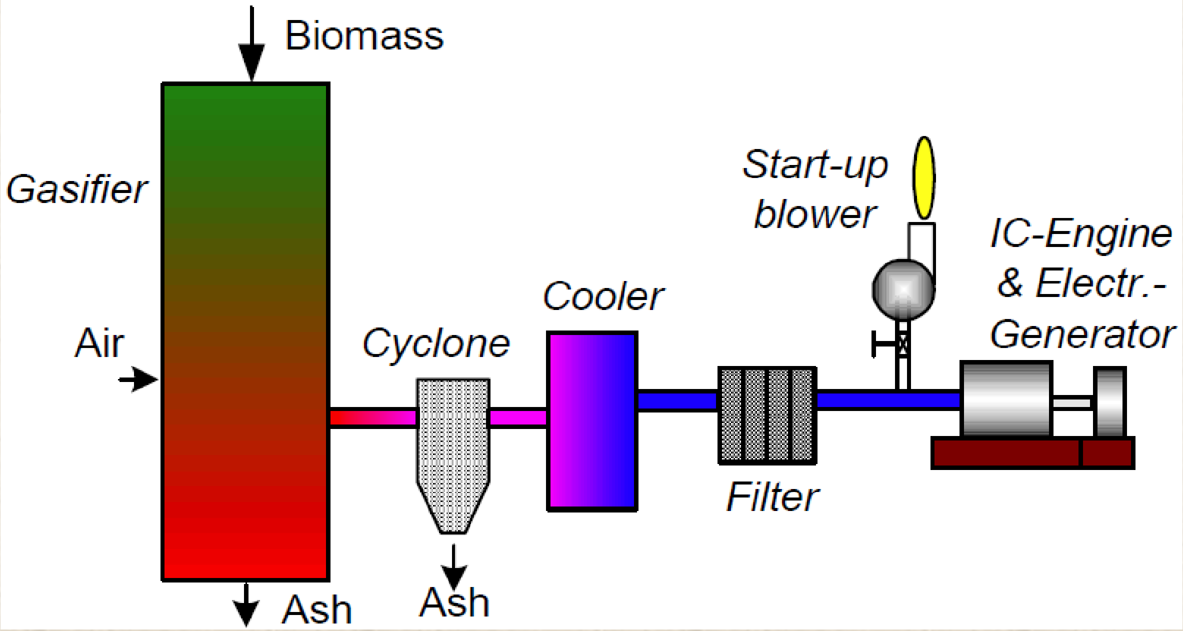
Closed-constricted Downdraft Gasifier



Gasifier types

Characteristics of Downdraft Gasifiers

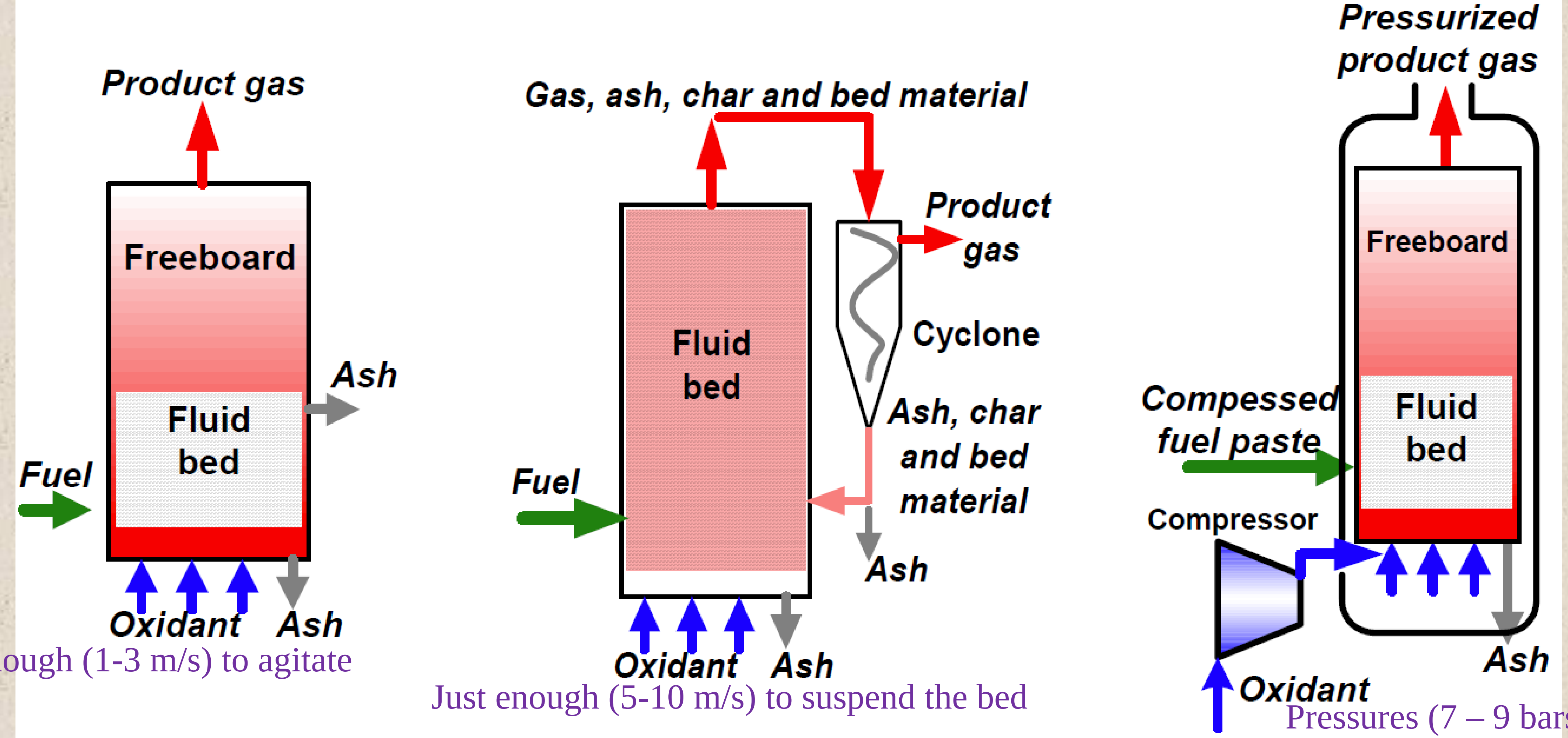
- The heat generated from combustion is used for the char reduction reactions, pyrolysis and drying
- For open-core, as the pyrolysis gases passes through a zone with very high temperature, the tars produced during pyrolysis will to a large extent crack to light compounds such as CO, CO2 and CH4
- As air is introduced with the biomass in the top, it is going to be present in the pyrolysis step, and thus flaming pyrolysis will take place, (i.e. simultaneously combustion of pyrolysis gases around the particle)
- The closed constricted gasifier concentrates the heat in the constriction, and gives thus very low tar content in the gas
- The large advantage with the open-core design is that it is more fuel flexible (size and shape) than the closed constricted type
- The product gas is suitable for IC-engine operation, for example powering small villages



Typical small-scale gasifier-engine power plant (5 – 100 kW)

Gasifier types

Fluidized bed Gasifiers



Just enough (1-3 m/s) to agitate

Just enough (5-10 m/s) to suspend the bed

Pressures (7 – 9 bars)

- A gas stream passes vertically upward through a bed of inert particulate material (sand) to form a turbulent mixture of gas and solid. Fuel is added at such a rate that it is only a few percent by weight of the bed inventory.
- No segregated regions of combustion, pyrolysis, and tar cracking exist. The violent stirring action makes the bed uniform in temperature and composition with the result that gasification occurs simultaneously at all locations in the bed

Gasifier types

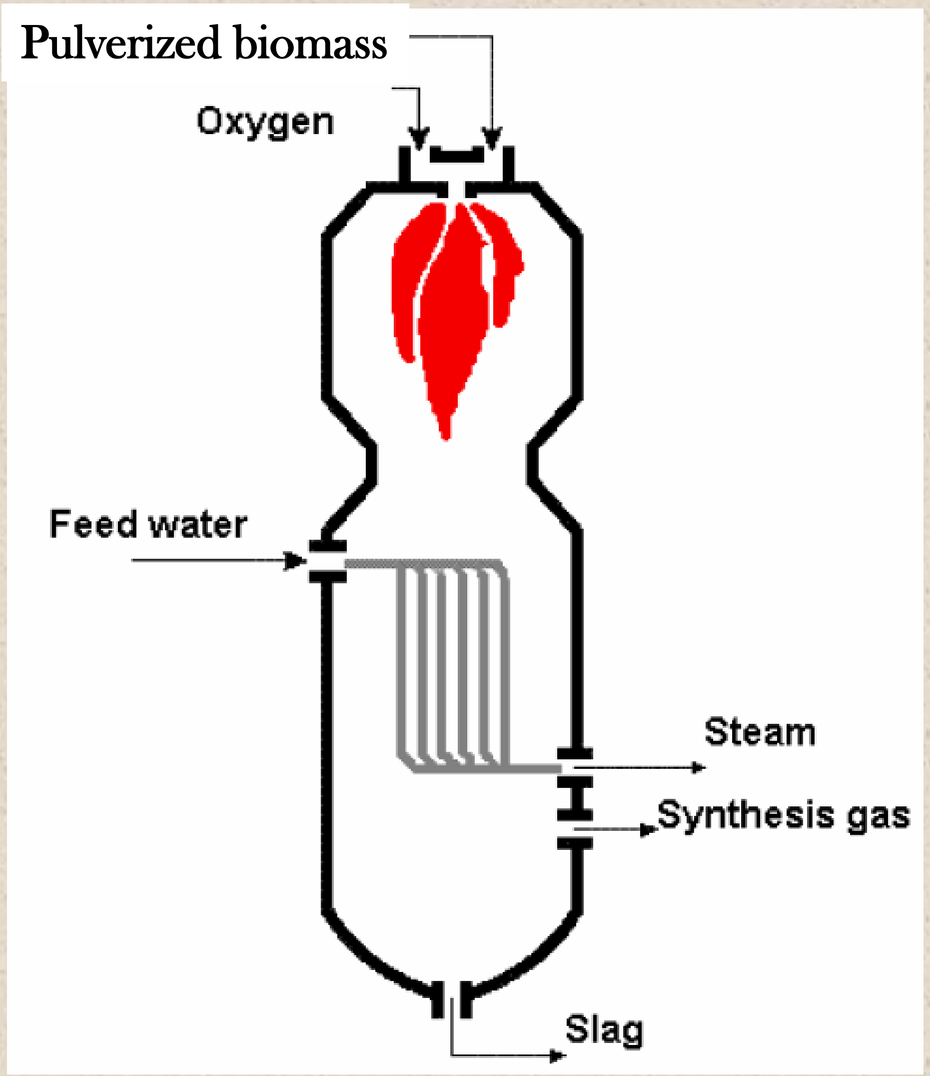
Characteristics of Fluidized bed Gasifiers

- **The fuel content is 2-3% of the bed material, the rest is inert particles**
- **Compared to fixed bed gasifiers, the gasification temperature is relatively low; an even temperature is selected in the range of 750°C to 900°C**
- **Compared to fixed bed gasifiers, the heating of the fuel during pyrolysis is faster and therefore the reactivity of the char is high**
- **Due to the intense mixing, the different reactions phases (drying, pyrolysis, oxidation, and reduction) can not be distinguished in separate zones**
- **Contrary to fixed bed gasifiers, the oxidizer-biomass ratio can be changed, and as a result the bed temperature can be controlled**
- **The product gas from a fluidized bed has a higher tar content compared to the downdraft as for the relative low operation temperature**
- **Low grade coals, wood chips, RDF (refuse derived fuel) and other fuel pellets are suitable**
- **An important application of fluidized beds are for use in larger scale power plants (steam plants *or* combined gas turbine and steam plants) or for synthesis gas production**

Gasifier types

Entrained flow Gasifiers

- Entrained flow reactors employ finely pulverized biomass and oxygen-steam as oxidizing agent in co-current flow
- High temperatures are achieved 1200 – 1500 ^{o}C
- The flow is extremely turbulent and the residence time is short
- Commonly used for coal because finer particle sizes and higher temperatures can be achieved
- Tar and methane are not present in the product gas. High content of H_2
- Ash is removed as slag because the operating temperature is well above ash fusion temperature
- More practical for low grade coal and high coal throughput
- Application: synthesis gas for methanol production or power generation (IGCC)



Gasifier types

Characteristics and features

Parameter	Downdraft	Updraft	CFB
Fuel			
-moisture content (%)	< 25	< 60	< 25
-ash content (%, daf)	<6	<25	<25
-size (mm)	20-100	5-100	<20
Gas			
- **temperature (°C)**	800	200-400	850
- **LHV (kJ/m_n^3)**	4-6	4-6	5-6,5
- **tar content (g/ m_n^3)**	0,01-6	10-150	2-30
- **particulates (g/ m_n^3)**	0,1-8	0,1-3	8-100
- **composition (% v/v.)**			
H_2	15-21	10-14	15-22
CO	10-22	15-20	13-15
CO_2	11-13	8-10	13-15
CH_4	1-5	2-3	2-4
Max commercial capacity (forecast) (MW_{th})	1	10	100
Scale-up ability	poor	good	v. good

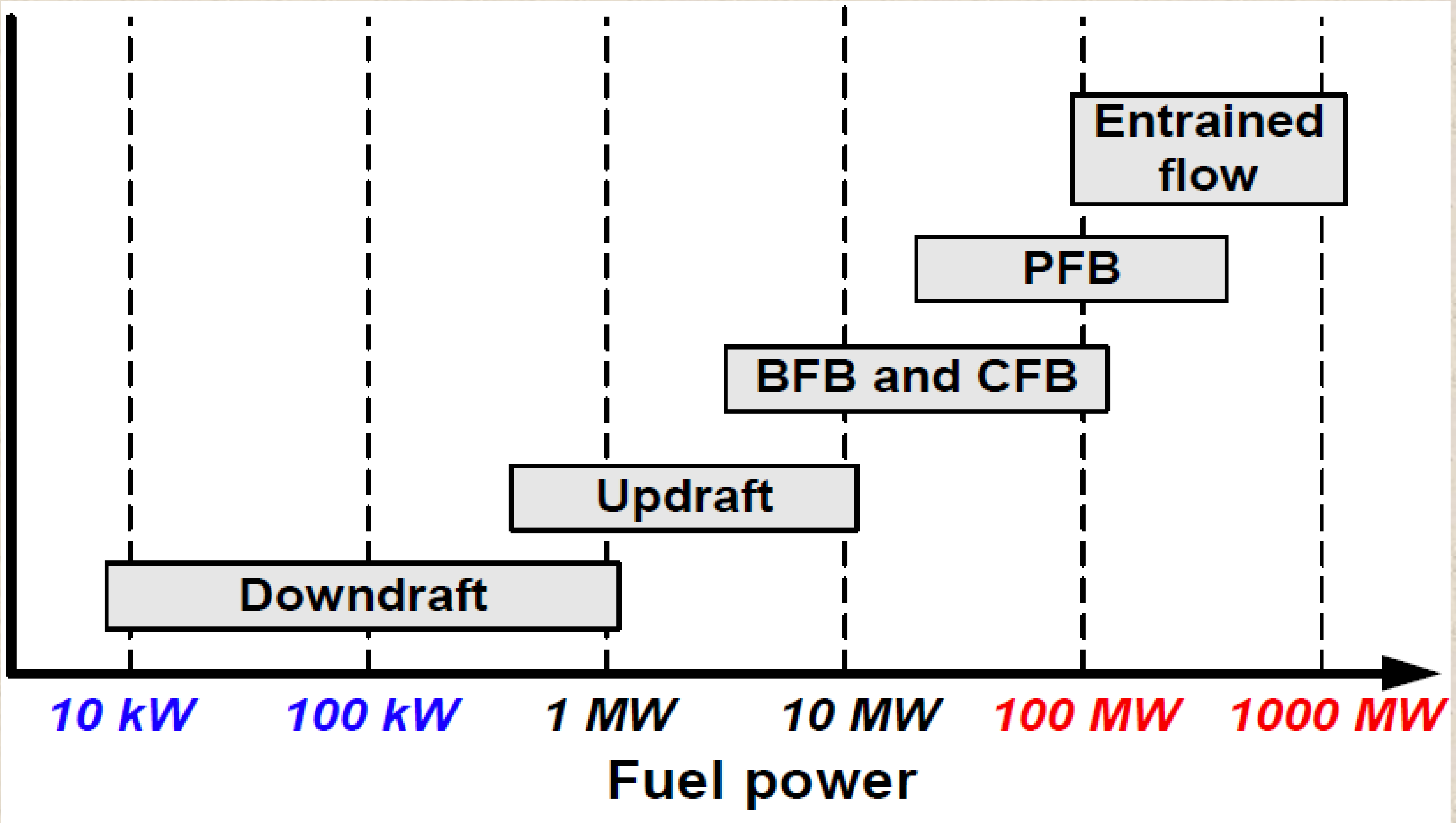
Gasifier types

Characteristics and features

PARAMETERS	FIXED BED			FLUID BED	
	Up-draft	Down-draft	Cross flow	Bubbling	Circulating
Reaction temperature [C]	1000	1000	900	850	850
Gas temperature [C]	250	800	900	800	850
Throughput [t/h]	10	0.5	1	10	50
Electric power [MWe]	1 - 10	0.1 - 5	0.1 - 2	1 - 20	2 - 100
	GAS CHARACTERISTIC				
Tars content	v. high	v. low	v. high	medium	low
Particulates	av. high	medium	high	v. high	v. high
	FEEDSTOCK REQUIRAMENTS				
Mixing intensity	low	low	low	good	v. good
Limits for particle size	some	some	some	specific	specific
Moisture content	any	limited	limited	limited	limited
Fuel flexibility	no effect	low effect	low effect	strong	strong
	DEVELOPMENT POTENTIAL				
Scaling up	limited	low	low	good	v. good
Process control	medium	medium	low	v. good	v. good
	EFFECTIVITY				
Conversion efficiency	v. good	v. good	low	good	v. good
Thermal efficiency	v. good	v. good	good	good	v. good

Gasifier types

Gasifier thermal power range



Gasifier types

Advantages and disadvantages

Gasifier	Advantages	Disadvantages
Updraft fixed bed	Mature for small-scale heat application Can handle high moisture No carbon in ash	Feed size limits High tar yields Scale limitations Low heating value Slagging potential
Downdraft fixed bed	Small-scale applications Low particulates Low tar	Feed size limits Scale limitations Low heating value Moisture sensitivity
Bubbling fluidized bed	Large-scale applications Feed characteristics Direct/indirect heating Gas with higher heating value	Medium tar yield Higher particle loading
Circulating fluidized bed	Large-scale applications Feed characteristics Gas with higher heating value	Medium tar yield Higher particle loading
Entrained flow fluidized bed	Can be scaled Potential for low tar Potential for low methane Gas with higher heating value	Large amount of carrier gas Higher particle loading Particle size limits

Gasification Performance

Typical producer gas composition and heating value of some agricultural feedstock

Biomass fuel	Gasification method	Composition (% Volume)					Heating Value (MJ/m^3)
		CO	H_2	CH_4	CO_2	N_2	
Charcoal	Downdraft	28 - 31	5 - 10	1 - 2	1 - 2	55 - 60	4.60-5.65
Charcoal	Updraft	30	19.7	-	3.6	46	5.98
Wood (10-20% MC)	Downdraft	17 - 22	16 - 20	2 - 3	10 - 15	55 - 60	5.00 - 5.86
Wheat straw pellets	Downdraft	14 - 17	17 - 19	-	11 - 14	-	4.50
Coconut husks	Downdraft	16 - 20	17 - 19.5	-	10 - 15	-	5.80
Coconut shells	Downdraft	19 - 24	10 - 15	-	11 - 15	-	7.20
Pressed sugarcane	Downdraft	15 - 18	15 - 18	-	12 - 14	-	5.30
Corn cobs	Downdraft	18.6	16.5	6.4	-	-	6.29
Paddy husks pellets	Downdraft	16.1	9.6	0.95	-	-	3.25
Cotton stalks cubed	Downdraft	15.7	11.7	3.4	-	-	4.32

Gasification Performance

Producer gas applications and quality requirement

Product	Synthetic Fuels	Methanol	Hydrogen	Fuel Gas	
	FT Gasoline & Diesel			Boiler	Turbine
H_2/CO	0.6 [a]	~2.0	High	Unimportant	Unimportant
CO_2	Low	Low [c]	Not Important [b]	Not Critical	Not Critical
Hydrocarbons	Low [d]	Low [d]	Low [d]	High	High
N_2	Low	Low	Low	Note [e]	Note [e]
H_2O	Low	Low	High [f]	Low	Note [g]
Contaminants	<1 ppm Sulfur Low Particulates	<1 ppm Sulfur Low Particulates	<1 ppm Sulfur Low Particulates	Note [k]	Low Part. Low Metals
Heating Value	Unimportant [h]	Unimportant [h]	Unimportant [h]	High [i]	High [i]
Pressure, bar	~20-30	~50 (liquid phase) ~140 (vapor phase)	~28	Low	~400
Temperature, ^{o}C	200-300 [j] 300-400	100-200	100-200	250	500-600

Gasification Performance

Gasifier Efficiency

- Performance of a gasifier is often expressed in terms of its efficiency, which can be defined in two different ways: cold gas efficiency and hot gas efficiency.
- The cold gas efficiency is used if the gas is used for running an internal combustion engine in which case it is cooled down to ambient temperature and tar vapors are removed from the gas.
- For thermal applications, the gas is not cooled before combustion and the sensible heat of the gas is also useful

$$\eta_{ceff} = (V_g C_g)/(M_b C_b)$$

V_g = gas flue generation rate (m^3/s)

C_g = heating value of the gas (kJ/m^3)

M_b = biomass consumption rate (kg/s)

C_b = calorific value of biomass (kJ/m^3)

Typical value: 70 %

$$\eta_{heff} = (V_g C_g + H_{sensible})/(M_b C_b)$$

$H_{sensible} = C_p V_g (t_g - t_a)$

t_g = gas temperature

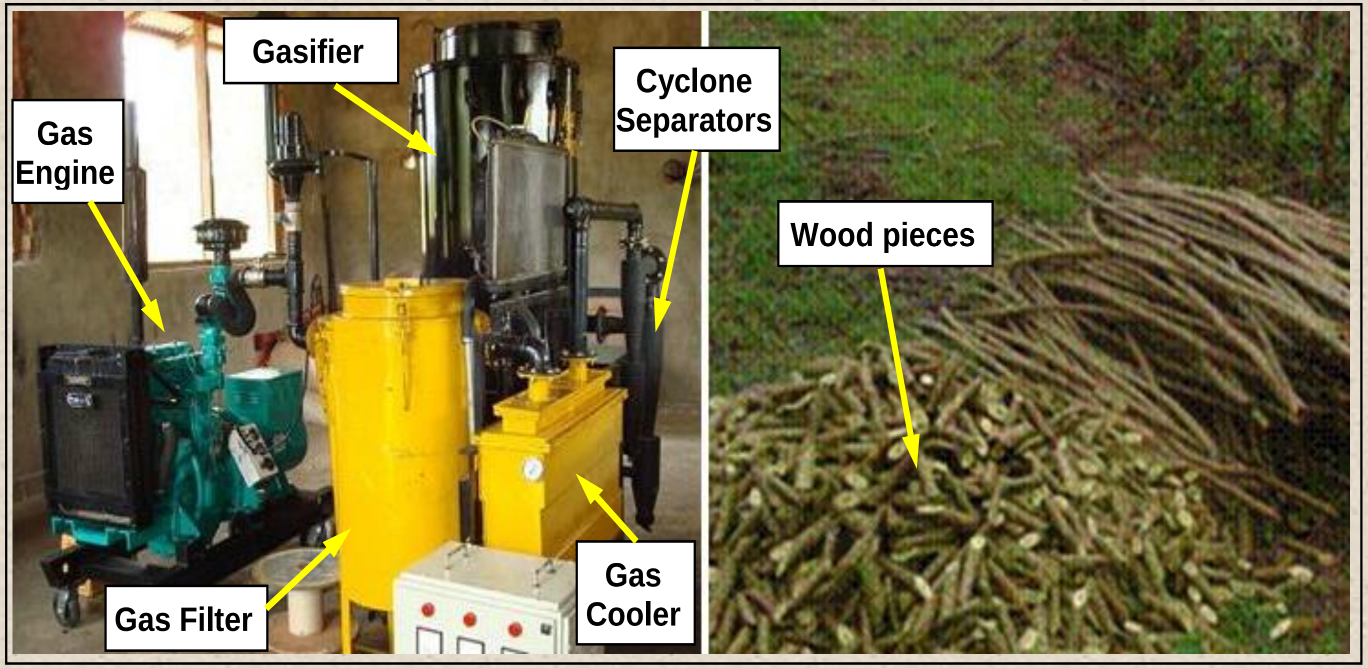
t_a = ambient temperature

Typical value: 75 %

Practical gasification systems

The two-burner rice husk gas stove - Philippines

Institutional Cookstove



3.5 kWe fuel wood gasifier - IC engine system in Sri Lanka

Industrial gasifier (2 MWth)

Small scale electricity generation

- ➢ **Introduction**

1. Energy Context
2. Biomass as Renewable Energy Resources
3. Bioenergy

- ➢ **Biomass characteristics**

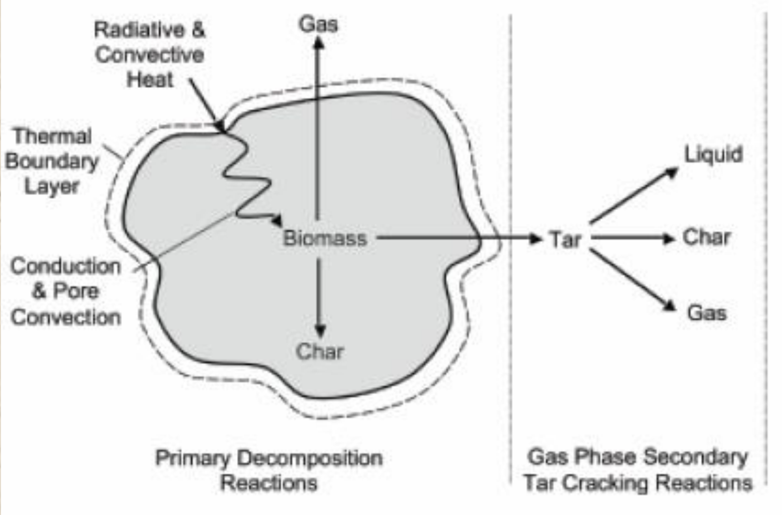
1. Biomass composition
2. Thermo-physical properties

➢ Biomass Thermal Conversion

1. Principals
2. Gasification technology
3. Pyrolysis technology

Principal of Pyrolysis

- Pyrolysis is a <u>thermal decomposition</u> by heat in the <u>absence of oxygen</u>

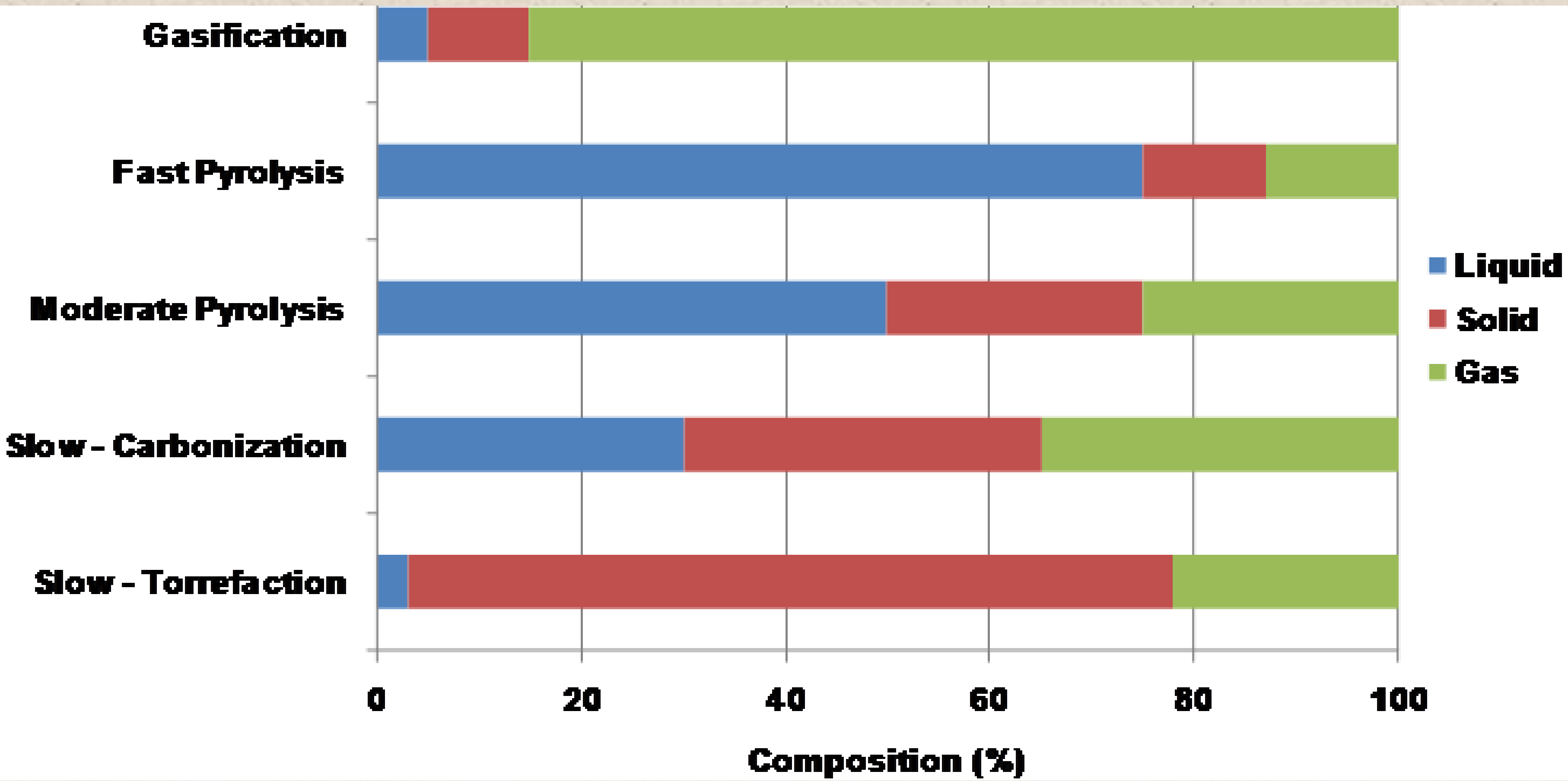


Dry Biomass → char + (CO, CO_2, H_2, H_2O (g), CH_4) + tars + Ash

- During pyrolysis biomass undergoes a sequence of changes and normally yields a mixture of gases (<u>Pyrolysis gas</u>), liquids (<u>Bio-oil</u>) and solid (<u>Charcoal</u>)
- The main purpose of pyrolysis is to produce <u>bio-oils</u> and <u>biochar</u>
- Generally low temperatures and slow heating rates results in high yield of charcoal. This type of pyrolysis is called <u>carbonization</u>
- <u>Liquefaction</u> can also be confused with pyrolysis.
- The two processes differ in operating parameters, requirement of catalyst, and final products.
- Liquefaction produces mainly liquid (Fast pyrolysis)

Pyrolysis Technology Variant

Percentage composition of liquid, solid and gaseous products of different pyrolysis modes



Pyrolysis Technology Variant

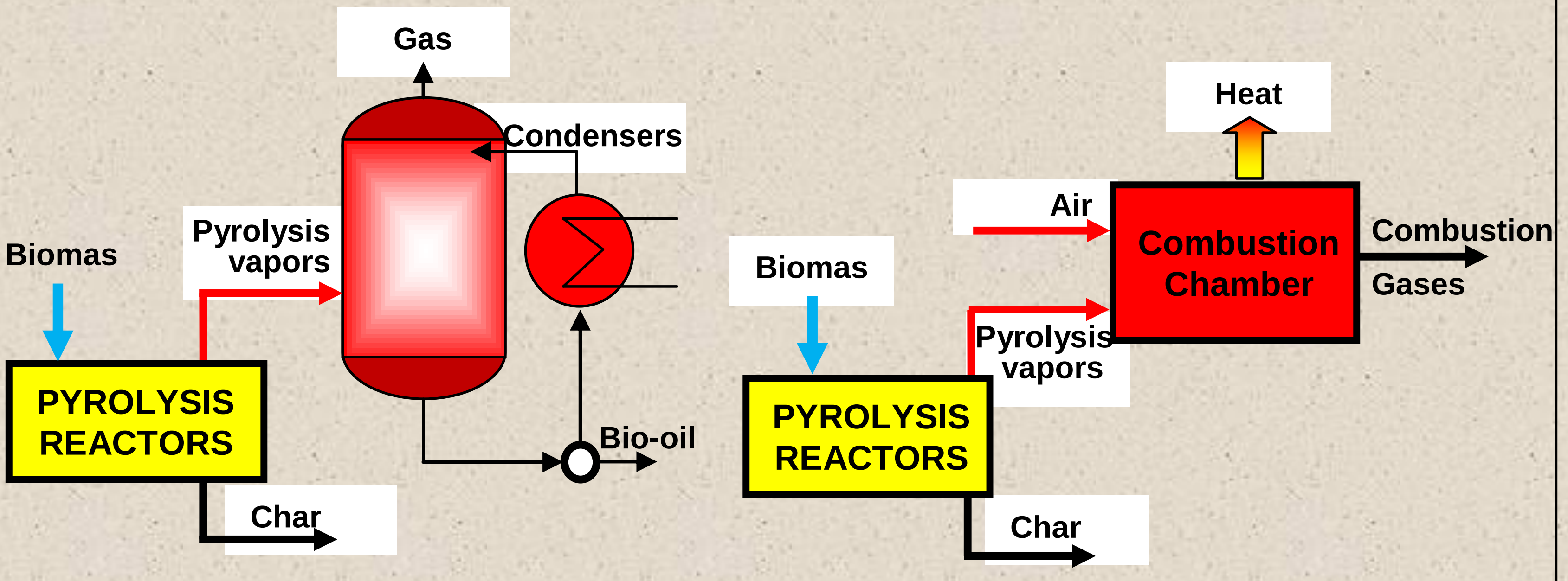
Pyrolysis processes classified based on heating rates and residence time

Process	Residence Time	Heating Rate	Temp (°C)	Products
Carbonization	Days	Very low	400	Charcoal
Conventional	5 – 30 min	Low	600	Oil, Gas, Char
Fast	0.5 – 5 sec	Very high	650	Bio-oil
Flash-liquid	< 1 sec	High	<650	Bio-oil
Flash-gas	< 1 sec	High	<650	Chemicals, Gas
Ultra	< 0.5 sec	Very high	1000	Chemicals, Gas
Vacuum	2- 30 sec	Medium	400	Bio-oil
Hydro-pyrolysis	< 10 sec	High	<500	Bio-oil
Methano-pyrolysis	< 10 sec	High	>700	Chemicals

Basic processes of Pyrolysis plant

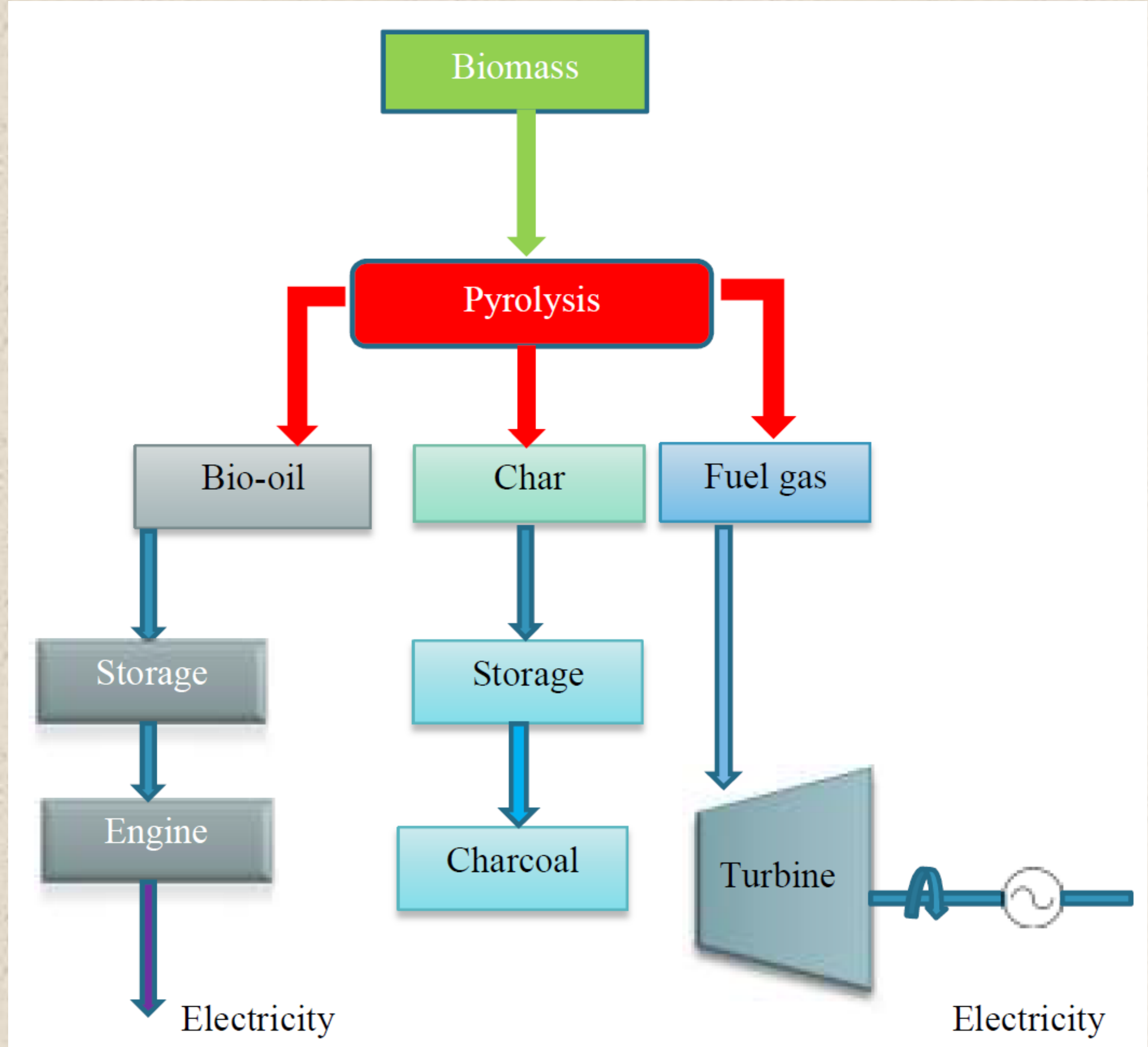
System Configuration

- A pyrolysis system unit typically consists of the equipment for biomass pre-processing, the pyrolysis reactor, and equipment for downstream processing.
- Can be classified as units that produce heat and biochar (using slow pyrolysis) or units that produce biochar and bio-oils (using fast pyrolysis),



(a) Biochar and bio-oil production (b) Biochar and heat production

Pyrolysis products / end-use

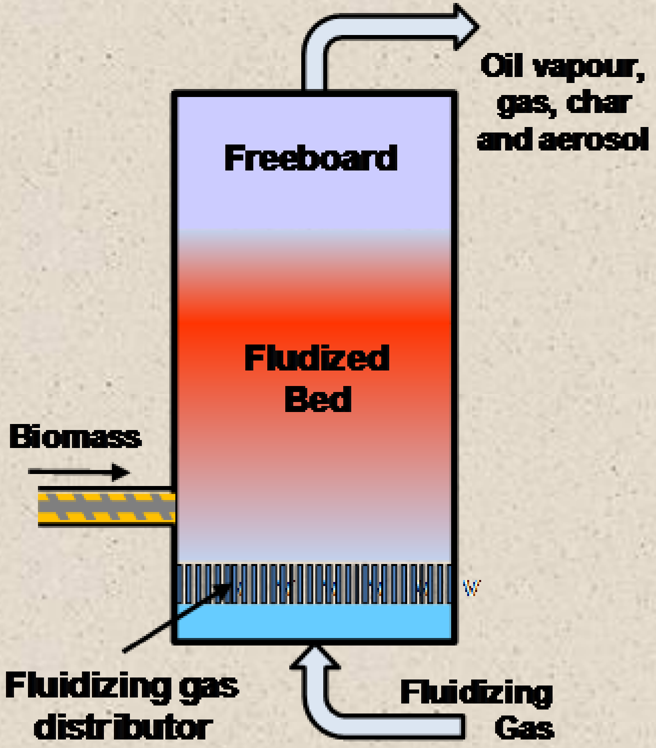


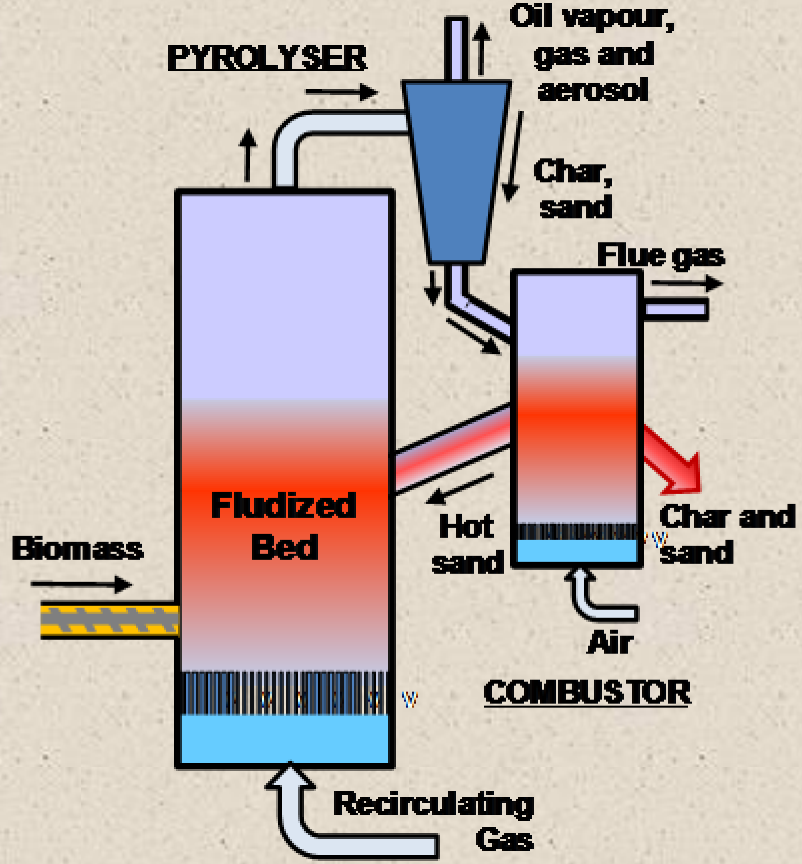
Typical Bio-oil vs Heavy Fuel

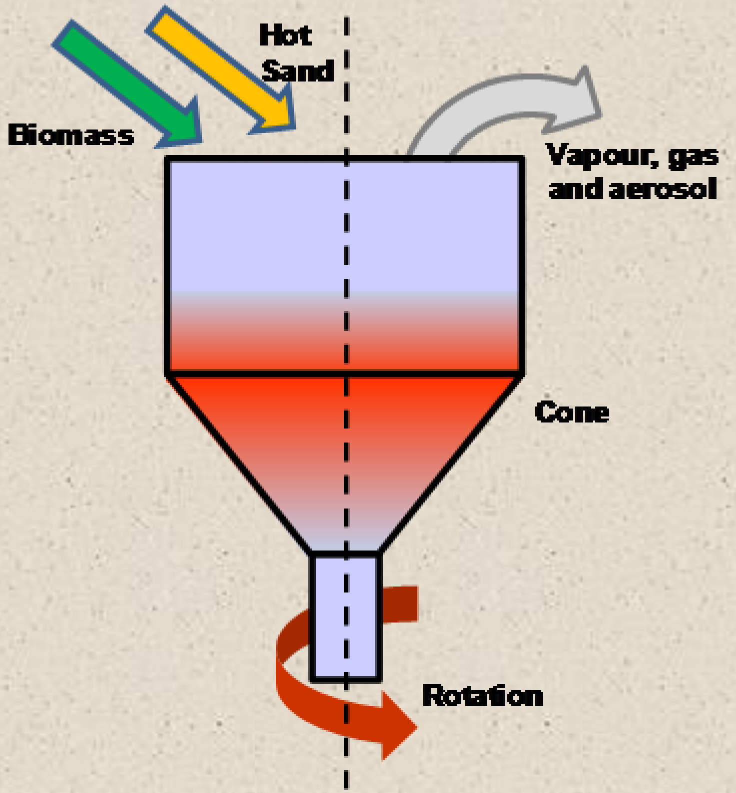
Physical property	Pyrolysis Bio-oil	Heavy Fuel Oil
Water, wt%	15-30	0.1
Specific Gravity	1.2	0.94
Heating Value (MJ/kg)	13-19	40
Solids, wt%	0.2-0.1	0.2-1.0
Viscosity, (at 50°C) (cP)	40-100	180
pH	2.5	
Oxygen, wt%	35-60	0.6-1.0

Types of Pyrolysis Reactor Designs

- A number of different pyrolysis reactor designs are available.
- These include Fluidized bed, Re-circulating fluidized bed, Ablative, Rotating cone, Auger (or screw), Vacuum, Transported bed, and Entrained flow.







Types of Pyrolysis Reactor Designs

- **As pyrolysis is a precursor to gasification and combustion, the same reactors used for gasification can be used for pyrolysis.**
- **Bubbling fluidized bed reactors are simpler to design and construct than other reactor designs, and have good gas to solids contact, good heat transfer, good temperature control, and a large heat storage capacity.**
- **Circulating fluidized bed pyrolysis reactors are similar to bubbling fluidized bed reactors but have shorter residence times for chars and vapors which results in higher gas velocities, faster vapor and char escape, and higher char content in the bio-oil.**
- **They have higher processing capacity, better gas-solid contact, and improved ability to handle solids that are difficult to fluidize.**

Types of Pyrolysis Reactor Designs

Reactor type	Status	Mode of heat transfer	Max. Yield Wt %	Typical features
Fluidized bed	Commercial	90% conduction; 9% convection; 1% radiation	75	**High heat transfer rates**; Heat supply to fluidizing gas or to bed directly; Limited char abrasion; Very good solids mixing; **Simple reactor configuration**; Particle size limit < 2 mm in smallest dimension
Circulating fluidized bed	Commercial	80% conduction; 19% convection; 1% radiation	75	**High heat transfer rates**; High char abrasion from biomass and char erosion; Leading to **high char in product**; Char/solid heat carrier separation required; Solids recycle required; Increased complexity of system; Maximum particle sizes up to 6 mm; Possible liquids cracking by hot solids; Possible catalytic activity from hot char; Greater reactor wear possible
Rotating cone	Pilot	95% conduction; 4% convection; 1% radiation	70	Low feedstock size; **Flexible feedstocks**; **Compact design**; Heat supply problematical; Heat transfer gas not required; Particulate transport gas not always required, Low particle content in bio-oil